INTERMITTENT WIND GENERATION: SUMMARY REPORT OF IMPACTS ON GRID SYSTEM OPERATIONS

CONSULTANT REPORT

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JUNE 1, 2004
500-04-091

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EXECUTIVE SUMMARY

Cumulative global wind energy production capacity reached 39,294 MW at the end of 2003. New wind power projects totaling 8,133 MW in capacity, were installed worldwide during 2003. This is an increase of 26 percent, according to estimates by the American Wind Energy Association (AWEA) and the European Wind Energy Association (EWEA). Wind power projects power the equivalent of 9 million average American homes (19 million average European homes) worldwide [66].

In this document we address the following questions:

1. What are the issues associated with large-scale wind integration and what empirical data do we have from Europe, Japan and the US?
2. How do system characteristics in Europe differ from the Western Electricity Coordinating Council (WECC) and the California Independent System Operator (CA ISO) systems?
3. How will wind generation affect the physical operations of the grid?

There are areas now in Europe that are very highly penetrated with intermittent wind generation. These include the Northern German transmission system (E.ON Netz and VE) and Denmark. In these areas more than 70 percent wind penetration is common under low loading conditions. The table below shows the installed penetration levels for some major wind generation regions at the end of 2003 [4],[47],[66].

Table 1: Example of Wind Systems and Installed Penetration Levels

Region	Peak Load MW	Installed Wind MW	Penetration
Denmark	3,800	3,100	62 percent
Germany	77,000	14,600	19 percent
Spain	36,000	6,200	17 percent
The Netherlands	14,000	1,000	7 percent
Continental USA	808,000	6,400	0.8 percent
Texas	63,000	1,900	3 percent
New Mexico	1,500	200	13 percent

The European experience showed us that during a relatively short period of just a few years, network reliability was maintained as this penetration developed. The network operations have adjusted to accommodate the change in generation mix. There are consequences of wind resources on network stability that have to be addressed as wind resources reach substantial levels of penetration. A list of the major issue categories follows:

1. New focus in system planning. Both steady state and dynamic planning considerations are important. Accurate forecasting becomes highly valuable.
2. Voltage support. Managing reactive power compensation is critical to grid stability.
3. Evolving operating rules. Sensitivity to generators providing regulation and minimizing start-stop operations for load following generators.
4. Equipment selection. Variable Speed Generation (VSG) turbines have the added advantage of independent regulation of active and reactive power. This type of turbine is preferred in new wind farm designs from a system operation perspective.

As Europe faces even larger amounts of wind penetration (goal is 75,000 MW in 2010, as shown by the line read on the right axis in Figure 1 [47]), network and system issues are becoming higher profile.

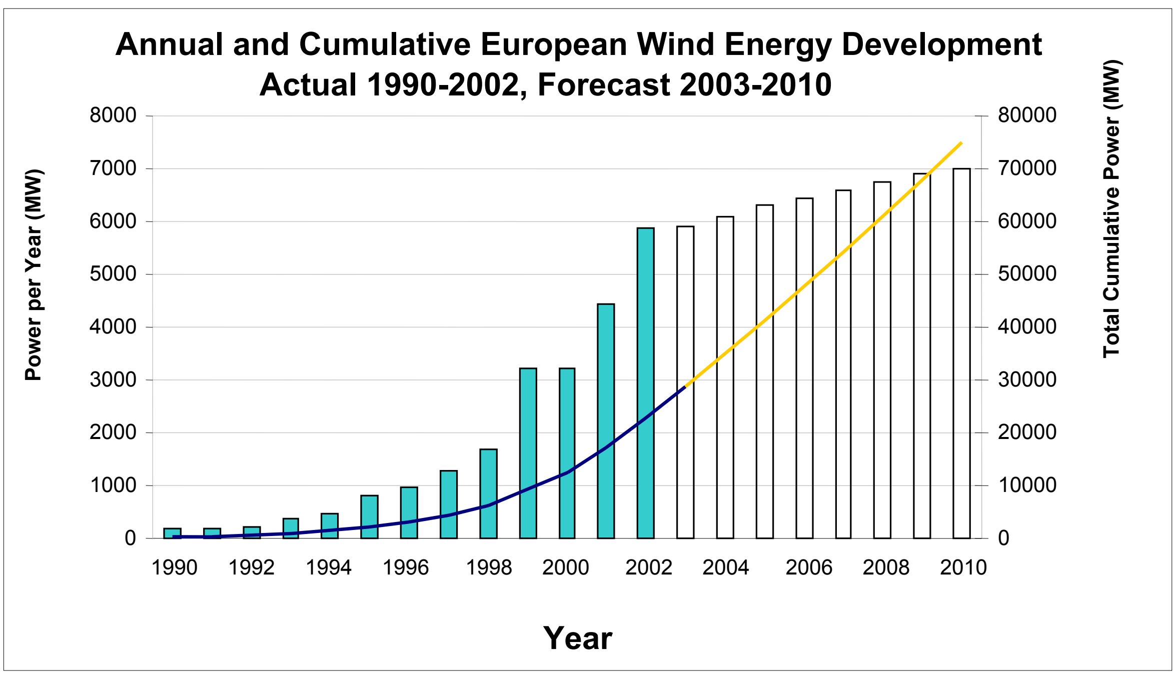

Figure 1. Development of European Wind Power Projects

Technical wind integration issues are not delaying efforts to reach this goal. However, focus has increased on planning and research to understand the needs of the system, for example, research is underway on energy storage options [35].

The United States has a different set of electric system characteristics than the WECC, but there is no experience or research in Europe that would lead us to think that it is technically impossible or even very challenging, to achieve 20 percent wind penetration in California. Long transmission distances between generation resources and load centers characterize the network in the WECC. But with modest, adequate measures, experience and research regarding offshore wind integration in Europe suggest that the 20 percent level of penetration is indeed possible.

Wind generator operation will affect the physical operation of the grid. The areas of focus include regulation, load following and broader system planning. The variability of wind regimes across resource areas, the lack of correlation between wind generation volatility and load volatility, and the size of the windplants relative to the system in the WECC and California suggest that impacts on regulation are small. Impacts on load following are larger and grow with penetration, but are well within the range of other system planning considerations. Over time, wind generator penetration will likely displace some existing and new thermal facilities.

The reference list at the end of this report is a very valuable compilation of work done to date on these subjects. The key conclusion of this set of work is that system operations can technically accommodate wind at penetrations far beyond the 20 percent of retail sales by 2010 from renewables including wind, as well as other eligible resources required for accelerated Renewables Portfolio System (RPS) compliance in California.

A consequential issue under study by the California Wind Energy Collaborative activity is the cost of integrating wind into the grid. Another issue being addressed at the California Public Utilities Commission (CPUC), CA ISO and WECC level, is the cost of network upgrades associated with wind and other new resources [47],[50],[54].

EXPERIENCES WITH INTERCONNECTING LARGE-SCALE WIND POWER

Introduction

In this section, existing studies, which provide empirical results of large-scale intermittent generation (wind) on grid operations, including dispatch, voltage support, ancillary services and congestion, are identified and summarized. The researched areas and regions include Germany, Denmark, The Netherlands, Spain, the UK and other European girds/control areas, as well as the United States of America. In addition, we searched for studies for the same geographic areas that forecast the system operational impacts of the addition of large-scale intermittent generation.

In Europe the total installed penetration of wind power is already around 10 percent of peak load, with some countries approaching penetration levels of 20 percent; Denmark has the highest penetration at 62 percent. Most studies on the network impact considerations of wind power are hypothetical and statistical. We were unable to uncover a comprehensive empirical study evaluating the impact of wind on system operations to date.

In most of the US regions the penetration of wind is still very low. Most areas have less than 5 percent penetration and, in principle, minimal impact on system reliability should be expected at these levels up to a level of 10 percent. At wind penetration levels of 10 percent to 20 percent, some adjustments to system operations may be required. Even at these levels, minimal impacts to high voltage transmission networks will be experienced. In the US wind power will likely be distributed throughout the network, with plant sizes of hundreds of megawatts. These blocks of wind power are most likely to be injected onto the distribution feeders. If larger blocks of wind power 500 MW to 1000 MW are added into only one or two network locations, these will be connected at transmission voltage levels and a transmission impact may be evident [65].

In the US, there are substantial, high-quality, untapped wind energy resources, and thus, mainly onshore wind power will be interconnected to existing networks. The integration of wind power with hydrogen as an energy carrier and storage technology has been debated in many forums, for example at the Hydrogen Economy workshop hosted in 2003 by the U.S. Department of Energy (DOE) [46]. The hydrogen economy is still a conceptual subject, but could address some of the shortcomings of wind power in the long term [29],[30],[31].

In some European countries, wind penetration is now proposed at the 20 percent to 40 percent levels for 2010 (75,000 MW goal), in conjunction with the planned decommissioning of thermal, especially nuclear, generation. This goal can only be met with large offshore wind farms in the Atlantic, North, and Baltic seas, interfaced with the existing power network in Northern Germany, The Netherlands, Spain, and France. The planning focus for wind power in Europe is now mainly focused to interface large amounts of wind power to the transmission system at voltage levels of 150 kV to 400 kV, connecting large offshore wind farms via AC and HVDC cables to onshore and offshore substations. Also under investigation are legal, commercial, and environmental issues associated with wind power operations in these busy marine traffic routes.

Under these high levels of wind penetration, impacts on system operation and transmission capacity could be expected. This is mainly due to the large penetration of wind power at one or two network connection points and the uncorrelated nature between wind generation and load that requires large amounts of balancing power for frequency control and stabilization. Assuming a wind power capacity factor of 30 percent, the reactive power requirements specifically associated with wind, as well as the power quality considerations (especially flicker), will require some mitigation effort during traditional and innovative transmission planning and upgrades.

One option currently being investigated to counteract some of these problems is the so-called “Wind and Water” model in which large-scale offshore wind power is balanced with pumped hydro storage. However, other energy storage and generation mixes are also investigated since using the wind and water model alone would be impractical given the size of Europe’s goals. For example it is not practical to increase the size of the pumped storage systems in the Alps by 18 times in order to compensate for low wind-speed durations and store energy for up to a week [21],[22]. Other generation or load management scenarios have to be implemented during low-wind times. In Europe, policy-makers assume that energy storage, including large-scale compressed air energy storage, is a precondition for any sustainable energy policy [14],[16],[17],[18], [19],[35].

Large-Scale Wind Power Impacts on Transmission Network

In Europe, substantial wind penetration exists today and will only increase over time. The impacts on the transmission network are viewed not as an obstacle to development, but rather as obstacles that must be overcome. High penetration of intermittent wind power (greater than 20 percent of generation meeting load) affects the network in the following ways and has to be studied in detail:

1. Power flow - Ensure that the interconnecting transmission or distribution lines will not be over-dutied. This type of analysis is needed to ensure that the introduction of additional generation will not overload the lines and other electrical equipment. Both active and reactive power requirements should be investigated. Reactive power should be generated not only at

the interconnection point partial private circuit (PCC), but also throughout the network, and should be compensated locally.

2. Short circuit - Determine the impact of additional generation sources to the short circuit current ratings of existing electrical equipment on the network.
3. Transient stability - dynamic behavior of the system during contingencies, sudden load changes and disturbances. Voltage and angular stability during these system disturbances are important. In most cases, fast-acting reactive-power compensation equipment, including SVCs and STATCOMs, are included for improving the transient stability of the network.
4. Electromagnetic transients – Ensure these fast operational switching transients have a detailed representation of the connected equipment, wind turbines, their controls and protections, the converters, and DC links.
5. Protection – Investigate how unintentional islanding and reverse power flow may have a large impact on existing protection schemes, philosophy, and settings.
6. Power leveling and energy balancing - Due to the fluctuating and uncontrollable nature of wind power as well as the uncorrelated generation from wind and load, wind power generation has to be balanced with other fast controllable generation sources. These include gas, hydro, or renewable power generating sources, as well as short and long-term energy storage, to smooth out fluctuating power from wind generators and increase the overall reliability and efficiency of the system. The costs associated with capital, operations, maintenance and generator stop-start cycles have to be taken into account as well.
7. Power Quality - Fluctuations in the wind power and the associated power transport (AC or DC), have direct consequences to the power quality. As a result, large voltage fluctuations may result in voltage variations outside the regulation limits, as well as violations on flicker and other power quality standards.

It is well-known from the existing “Near-Shore” and large-scale onshore wind power installations in the Scandinavian countries, that utilization of unmitigated large-scale wind power can result in network instability if the installed wind power capacity is higher than 20 percent of the instantaneous loading conditions [37],[39],[36]. In cases where the total wind power is higher than this percentage, innovative dynamic compensation solutions are required to operate the network, including Flexible AC Transmission Systems (FACTS) and energy storage.

Offshore Versus Onshore Wind Power Characteristics

Wind farms located offshore are planned in Europe because of higher average wind speeds on the North Sea and space limitations onshore. For most of the planned US installations, onshore projects will use variable speed generator

(VSG) turbines. The first offshore wind plant was recently announced in New York: 39 offshore wind turbines are planned for the Long Island Power Authority in the Atlantic Ocean.

Offshore wind farms will be different from their onshore counterparts: the turbines will on average have larger diameters and power output. The economical ratings of these turbines will be higher, in the 2 MW to 6 MW power range. Less turbulence offshore allows the turbines to harvest energy more effectively and lower wind shear, allowing the use of shorter tower structures. The farm will be difficult to access during periods with high winds, and erection and maintenance will be more expensive. The turbine noise may be a less sensitive issue. One of the major challenges is the submarine electrical connection to shore and its impact on the network. Proposals of 400 kV marine substations and HVDC links to offshore sub-station platforms are being considered [32].

For these proposed large offshore projects, the network interface might be a large factor for moving forward. The issues associated with dynamic stability, short-circuit power, network upgrades, power balancing between the wind farms and other independent power producers, import, export and natural loading on high-voltage networks are fundamental considerations to be solved. Parties are working on resolving the regulatory and legal issues related to these large fluctuating power sources as well.

Technological solutions exist or are currently in development to mitigate some of the above-mentioned problems. The technology trends in this regard include new voltage-source converter-based HVDC developments, flow-battery and compressed air storage options, wind turbine design improvements, direct drives, power electronic converters and control options.

Danish Wind Power Development

Wind Power Development

Denmark has a few key characteristics that mitigate its status as the jurisdiction with the highest penetration of wind in the world with installed capacity equaling 62 percent of peak load and serving 40 percent of demand: [69]

- It is located at the nexis of the hydro system of the Nordic system and thermal system of Germany;
- Its wind and wind plants are well dispersed across the country;
- Its load variation is higher than in neighboring regions. [68]

Denmark has not only the largest penetration of wind in its system; it is also a leader in offshore wind development which will change its system operations.

The most important implementation area for offshore wind energy today is in Northwest Europe. This area is densely populated, so there is not enough space for onshore wind power to meet countries' individual and EU-wide renewables targets. The coastal waters are relatively shallow, helping to make offshore wind energy technically and financially feasible.

When looking at the Danish wind market in the Nordic Power Pool (NPP), it is expected that 100 percent of Denmark's electric energy may come from wind and combined heat and power (CHP) in the future. Technical issues have not been viewed as an obstacle to meeting that policy. Instead, work is being done to answer key questions such as what level of forecasting accuracy will be available for predicting future wind power production [13].

Denmark has recently built an offshore wind farm (Horns Rev, 160 MW) and a second one is in an advanced stage of planning (Rødsand, 151-158 MW), see Figure 2 [36]. These two wind farms are still under the incentives policy of the previous Danish government. In the report *ENERGY 21*, prepared under the direction of the previous Danish government, 4,500 MW of offshore wind power is the target for 2030 [14]. The previous Danish government and network operators subsidized most of the financial consequences of wind power in the past. The realization of these targets is doubtful in the short-term, due to the changes in policy of the Danish government that have reduced wind subsidies.

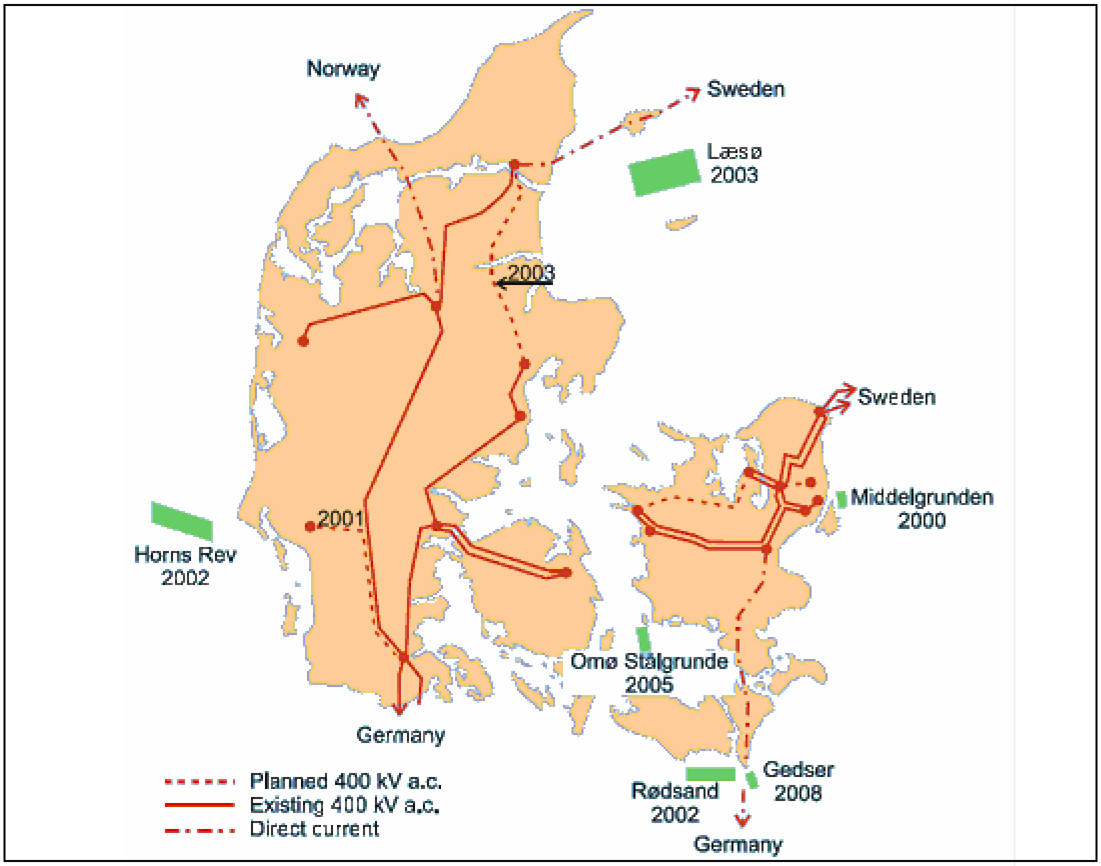

Figure 2. Offshore Wind Farm Plans in Denmark [36]

Maintaining Power and Energy Balance

Denmark uses wind power on a large-scale and has the highest percentage of wind power to load demand in the world. During low load conditions, wind power generation makes up 60 - 70 percent of the total load power with instantaneous values near to 100 percent, creating challenges to system operations, maintaining power and energy balances [27], [37] and selling wind power on the spot market. Until a change in government in 2001, Denmark considered wind power to be a priority and guaranteed a fixed price per MWh delivered (feed-in tariff). This guaranteed income was sufficient to grow the wind generation substantially to over 3,000 MW from under 1,000 MW in 1995 [66].

The network operator closest to the wind farm is obligated to connect the specific wind farm and to buy the generated wind energy at a guaranteed tariff. The original tariff structure provided a higher fixed-priced tariff for a minimum five-year period, and then a lower fixed-price tariff for the remaining 20 years after the wind farm becomes operational. The costs, involved with integrating wind-generated power, are assigned pro-rata to the two network operators in Denmark. The division of these costs is based on the total generation in the specific network. The supply operators are then obligated to buy this renewable energy at the average pool price (total cost price of all network operators).

Costs Associated with Network Upgrades

The wind farm owner or developer pays for the network connection. If a grid upgrade is required, the network operator is obligated to do it. The involved costs may be recovered from all the other network users, via the transport tariffs. This means that the financial risk for owners/developers is low. The uncertainty of the generation and the power fluctuation costs are not the responsibility of the wind farm operator.

Both network operators in Denmark have large quantities of wind power in their portfolio. The Danish approach has had the following advantages:

- Because the supplied energy price is fixed for a longer period, the developer can easily estimate the financial income of a wind farm by using the wind speed measurements and the power curve of the operating turbines. In this way the financial risks are limited. The short- and long-term power fluctuations and associated variations of electricity prices do not have to be considered in the feasibility study. No wind timing prediction is required and the fluctuating imbalance prices need not be considered.
- Because of the purchase obligation of the electricity operators, all costs associated with maintaining the power balance, to accommodate the extra wind power, is divided between all consumers and shareholders. The total costs are still the same, but because of the increased number of involved parties, the amount to be paid by each, is considerably less.

These factors are partly responsible for the high penetration and strong growth of wind energy in Denmark, compared to some other European countries, including The Netherlands. Furthermore, Denmark offers fast procedures for environmental permitting, also supporting the increase in the rate of wind power installations.

United Kingdom Wind Power Developments

Over the past several years, the United Kingdom has begun to tap its wind power potential but has not yet faced issues of large-scale wind integration. However, the UK aims to increase the existing 649 MW installed wind power projects to 2,600 MW of wind power installations by 2010. The expectation is that plants will be built mainly offshore, supplying at least 10 percent of the UK electricity requirements. Planning for these offshore plants is in progress.

The UK government issued 18 permits to build offshore wind farms. Each permit allows the building of thirty turbines [50]. The permits are distributed to a large number of project developers, which are now developing the sites. Currently, two of these offshore turbines in the wind farm Blyth Harbor are operational, shown in Figure 3. These are two 2 MW turbines, 1 km offshore.

Figure 3. Two 2 MW Offshore Turbines at Blyth Harbor, 1 km Offshore [50].

Dutch Wind Power Developments

Wind Power Development

The peak load of the Netherlands is roughly 14,000 MW and the installed peak wind capacity is about 1,000 MW: a ratio of around 7 percent [4],[47],[66]. However, several feasibility studies and demonstration on-shore and offshore wind farm installations are currently planned which may affect the high voltage network when the percentage of wind power increases to 20 percent or higher. Furthermore, several neighboring countries like Germany, Belgium and Spain are installing wind power on a large scale that may, in aggregate, have an impact on the operation of the Dutch high-voltage networks [21],[22].

The North Sea wind resource provides the key to meet the Dutch government's goal to produce 6,000 MW of wind power by the year 2020 from offshore wind energy. It is clear that this amount of wind power will have some consequences for the network stability and system operations of the Dutch network operator (TenneT). Research on the technical, organizational, economic and legal consequences for this decision is underway. A first step in this direction was taken in a pre-feasibility study preformed by KEMA for the Dutch government with contributions from the different network operators in the Netherlands [45]. A network map has been developed to quantify the required network upgrades, short and long term energy balance policies, some trading and regulation mechanisms and legal issues in developing such a wind resource.

Maximum electricity demand is expected to grow to around 23,000 MW in 2020. The 6,000 MW offshore wind power can be interfaced to the Dutch 380 kV network at different locations, and it is expected that the wind power will be distributed among at least two, but probably three, locations of 2,000 MW and 3,000 MW each. These different scenarios have been studied using load-flow studies. These scenarios were calculated using zero and 5,000 MW import/export conditions to neighboring countries (Belgium and Germany).

Program Responsible Party

In the Netherlands the different parties involved in a specific wind power project, via a Program Responsible Party (PRP) agreement, are responsible for all the costs associated with the wind power project, including the additional costs for maintaining the short and long-term power and energy balances [49],[45]. The specific network system operator, through special connection tariffs, can subsidize a part of these financial consequences.

Maintaining Power and Energy Balance

Long-term power balance (from fifteen minutes up to days) is influenced by wind speed variations, because the generated power depends on the dominating wind speeds. In a period of fifteen minutes, substantial fluctuations can occur. The size of these fluctuations coincides also with the geographic distances between the individual offshore wind turbines combined in the different wind farms. On a time scale of hours to days, the wind power can fluctuate between zero and the nominal value of 6,000 MW.

The long-term power balance can be maintained by:

- Adjusting the operational philosophy of offshore wind farms.
- Controlling the electricity demand.
- Deploying large-scale energy storage systems.
- Adjusting the operating philosophy of conventional power generation units and eventually the diversity of the energy production.

Conventional generation units can be used to compensate for these long-term power fluctuations. However, using conventional generation for compensation will increase the number of start-stop cycles and thus the generators' maintenance and operational costs. These measures have to be implemented by the Program Responsible Party or by the Transmission System Operator, TenneT, by means of control and reserve power allocations. This has consequences for operational cost allocation to the different parties involved.

Impact on Network Upgrades and Reinforcements

A result of the 6,000 MW wind interconnection study [45] is a number of network upgrades at sub-stations, and new 380 kV interconnections are proposed. These changes to the 380 kV network are shown as the dashed orange, yellow, and purple sections of the network diagram of Figure 4. Furthermore, to maintain good reactive-power balance and voltage regulation throughout the network, several large capacitor banks should be added to the 380 kV sub-stations. Taking all these network upgrades into account, the 6,000 MW can be interfaced on a load-flow basis. Some more detailed dynamic studies are to be done and some wind-energy load forecasting has to be developed for this level of wind power penetration.

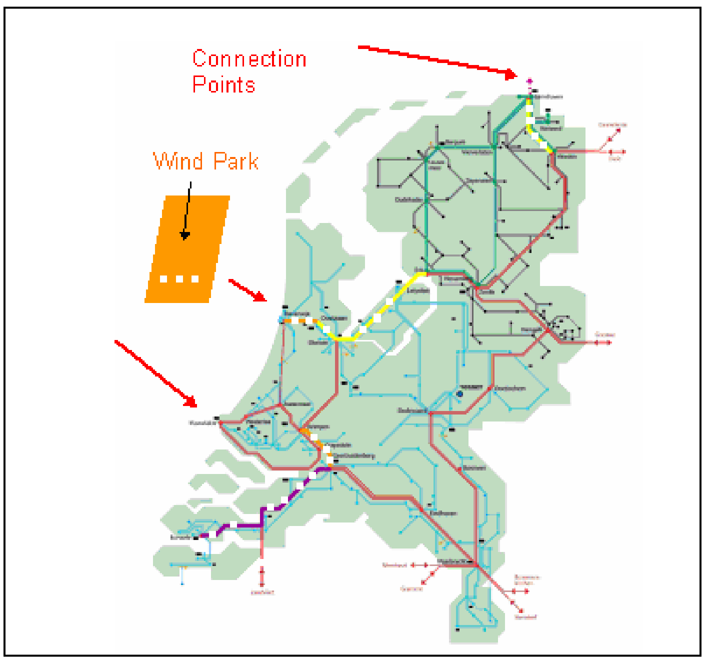

Figure 4. Major Dutch HV Network Upgrades for Interconnection of a 6,000 MW Offshore Wind Park in the North Sea [45].

When calculating the costs of these network upgrades, figures between €350 million and €650 million, depending on the scenario, can be expected in the network upgrades alone. If the increased demand is served instead with regular gas or nuclear generators, the required network upgrades may be less than €100 million. This implies a cost penalty to the upgrade of the electrical network infrastructure of €250 million to € 550 million if a 6,000 MW wind farm is to be erected on the North Sea coast. The total investment required for network upgrades is, however, still a very small percentage of the total wind park cost, estimated at roughly 4 percent of the total 6,000 MW wind park investment of €10 billion.

Wind Power Forecasting

Forecasting of the expected wind power is crucial for the Dutch system. Forecasting will not reduce the fluctuations, but reduces the uncertainty that coincides with the application of wind energy. Good forecast data is important for predicting the generated wind power. At this moment, this data is not available in the Netherlands. It is not easy to obtain this data either, because of the large number of parties that have to be involved (turbine owners, grid operators, energy companies, etc.).

German Wind Power Developments

Wind Power Development

The Renewable Energy Law (EEG), "Law for the Priority of Renewable Energies", came into force on April 1, 2000 to stimulate the use of renewable energy in Germany. The aim of this law is to at least double the proportion of renewable energy used for total energy consumption by 2010. Germany is already generating wind power on a large scale: 14,000 MW in 2003. In Germany, wind energy is considered to be a high priority and a long-term fixed price is guaranteed to the generator. The network operators and government subsidize wind energy risks, including the costs caused by the fluctuations of the wind power.

The network operator closest to the wind farm is obligated to connect the specific wind farm and to buy the generated power at a guaranteed tariff until at least 2020 [42]. The first period of generation receives a higher tariff, while the remaining period receives a fixed lower tariff rate. The length of the first period depends on the wind conditions at the specific site. If the energy production of the wind turbines is low, the high-tariff period is longer. For offshore wind farms, a period of 9 years for the high-tariff period is standard.

In Germany, there is currently an elevated tariff for offshore wind power development relative to onshore projects, as well as a favorable financing policy. Not surprisingly, 60,000 MW offshore wind power is now in the planning stage. To qualify for the favorable financing policy, the wind farms must be connected to the grid before 2007 [48].

Maintaining Power and Energy Balance

The costs involved with integrating wind power have been divided pro-rata among the network operators in Germany. The division of these costs is based on the total generation in the specific grid. The network operators are then obligated to buy this renewable energy at the average pool price (total cost price to all network operators). The renewable energy that individual supply operators can buy is determined by the contribution of renewable generators in the total energy generated, combined with the total operator supplied volume. The owner pays for the connection of the installation with the network.

The feed-in of wind power to the E.ON Netz, the largest network operator in Germany, is plotted for November 2001 in Figure 5 [42]. It is clear that large variations in wind energy production have to be accommodated on their system. Both daily and weekly variations of wind power and load have to be balanced on short and long term.

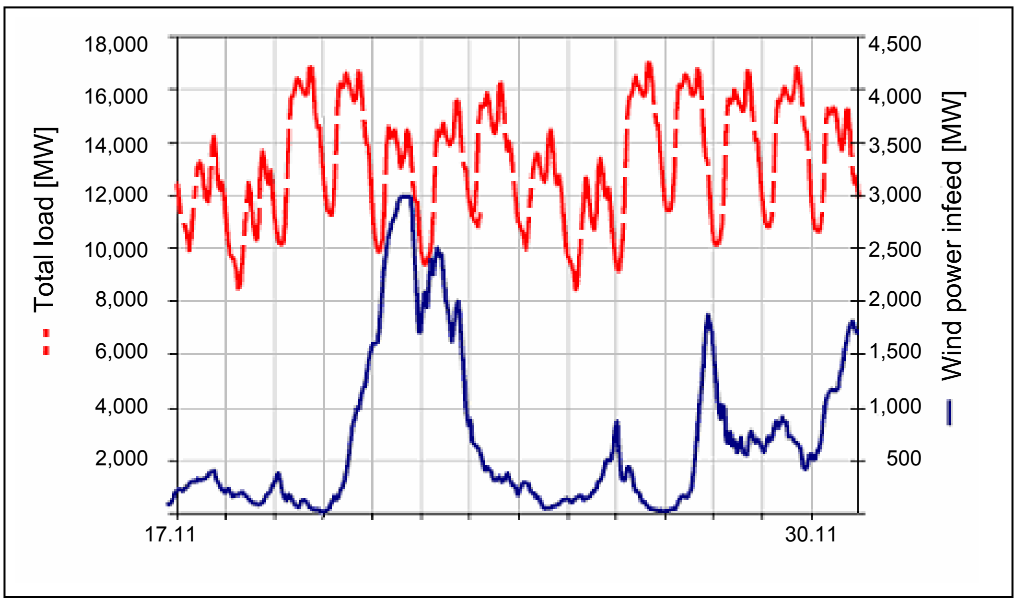

Figure 5. Consumption and Infeed of Wind Energy in the E.ON-Netz Region in November 2001 [42]

Stochastic wind generation can temporarily serve 90 percent of load. In order to operate the system, a wind-forecasting algorithm was developed at E.ON to predict the wind power for two days in advance.

Impact on Network Upgrades

The low capacity factor of wind power means that large wind power may often require some extra network upgrades in terms of new lines and cables, reactive power compensation and stability considerations. These extra network upgrade costs associated with renewable energies are divided uniformly throughout Germany and must be paid for by all electricity customers. If a network upgrade is required, the network operator is obligated to do it. The costs can be recovered from all users, via the transport tariffs.

This means that the financial risk for owners/developers is considerably lower than in the Dutch system. The uncertainty of the generation and the power fluctuation costs are not the responsibility of the wind farm operator. Rather, the extra costs for the system operation and the upgrade of the power grid are divided between all German grid and power operators, as well as all consumers.

At E.ON Netz, new wind power interconnection specifications have recently been developed [43]. These specification force wind turbines to stay connected to the network under unstable conditions, including sags in the supply voltage (Low Voltage Ride Through). For E.ON there are now additional charges for a wind power connection, including balancing the fluctuating power from the wind plants. The planning, construction and maintenance of lines and other network equipment for transporting the wind energy are also paid by the wind power developer.

Spain Wind Power Developments

Spain installed 1,377 MW of new wind capacity in 2003, with the cumulative wind power capacity reaching 6,202 MW by year's end. Wind now provides between 4 percent and 5 percent of Spain’s power. The peak load power is 33,000 MW.

Over the past decade, Spain's wind power fleet has grown from just 52 MW in 1993, in Tarifa across the straits of Gibraltar from Morocco, to over 6,000 MW, operating in several provinces, including Galicia, Aragon, Navarra and Castilla. The rapid growth was triggered by a federal requirement that utilities pay a premium price for electricity from wind over the first five years of the project—an incentive similar to the feed-in tariff that spurred the German wind energy market. Local governments have also required that a large share of the investment (such as manufacturing and construction) remain in the local economy.

Japanese Wind Power Developments

Wind Power Development

Japan has a peak load of roughly 175,000 MW and 686 MW of total wind capacity. Wind capacity has increased by an order of magnitude in Japan in the last five years and Japan plans for a more than 30- fold increase in the amount of wind capacity over a 10-year period. The driving force for this change was the adoption by the Japanese Government of a Renewable Portfolio Standard (RPS) system, which was made law in 2003. The purpose for adopting this system was to reduce the country's dependence on imported oil and to further reduce emissions from greenhouse gases in Japan.

Under the Japanese RPS system, a specific utility or power generating company can meet its RPS obligation by:

1. generating additional energy using renewable resources;
2. purchasing power produced by other companies that was generated by renewable resources; or
3. trading with other companies.

Under a trading arrangement, a given utility might decrease its RPS quota by reaching agreement with a neighboring utility to increase its RPS quota. Because of the small geographic scale of Japan, such a trading solution is more environmentally acceptable than it might be in a large country, such as the United States.

Maintaining Power and Energy Balance

The key technical challenge Japan faces in integrating additional wind generation is the need to balance power and energy output with customer demand on an hour-by-hour basis, as well as on an instantaneous basis. Because of the geography of Japan and the relatively small size of its grid, regulating frequency is a more significant problem than in most parts of the United States. Therefore, frequency regulation is probably the largest challenge of a technical nature that Japan faces in integrating additional wind resources. Other challenges that have been cited by the Japanese include voltage fluctuation, problems in coordinating system protection devices, and the need to control harmonic distortion.

Frequency problems in Japan are most pronounced on the island systems that are not part of the major grid that serves Tokyo, Osaka, and Kyoto. For example, the utility for Hokkaido faces frequency fluctuations that are illustrated in Figure 6. As the figure shows, when the frequency for their relatively smaller island grid with a 250 MW wind energy conversion (WEC) systems is compared to frequency variations with no wind energy resources, the amount of frequency variation is much greater.

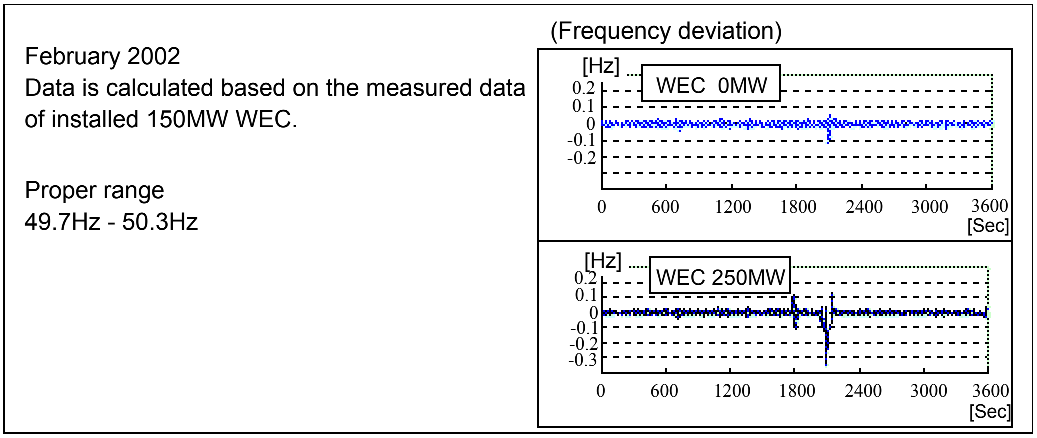

Figure 6. Sample Study on the Marginal Capability of Wind Energy Conversion (WEC) Systems from the Viewpoint of Frequency Control. Source: Hokkaido EPCO, Japan

One specific counter-measure to address the frequency regulation challenge is the use of mechanical flywheel energy storage. Figure 7 illustrates the effect of flywheel output on local frequency response for an experimental system in Japan.

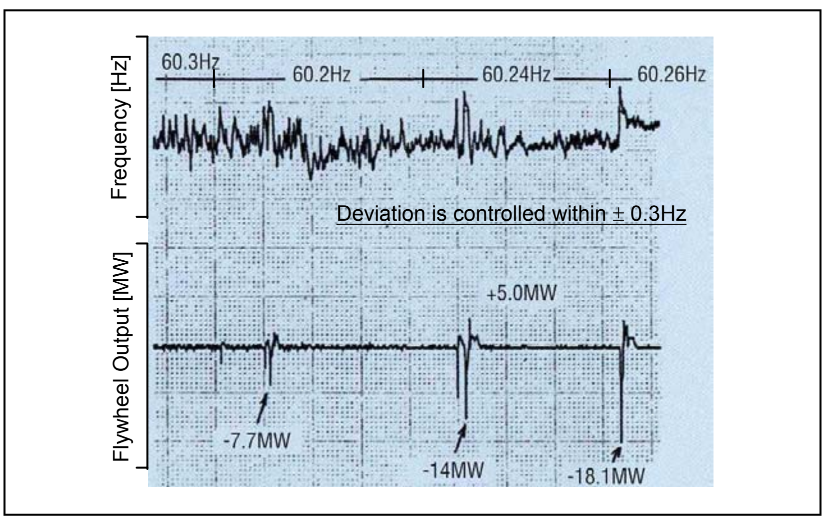

Figure 7. Stabilization of Frequency by ROTES. Source: Okinawa EPCO, Japan

Voltage fluctuations can occur as a result of generation output variations, especially when the wind resources are located in areas remote from the major transmission grid and load centers. Figure 8 shows an output leveling system that was designed to take advantage of Redox Flow (RF) battery storage to reduce the power flow variations in the local area of a wind generator. If economically feasible, such systems have great potential in Japan, especially for remotely-sited wind facilities.

In summary, Japanese engineers see numerous solutions to the system problems presented by expanding wind power generation in their country. However, there is a desire to slow the country's aggressive plan for increasing wind generation capacity in order to address some of these technical challenges in advance. Some actual field results of these impacts have already been made in Japan, and there is a desire on the part of the engineering community to further test the various counter-measures that have been devised to mitigate these effects.

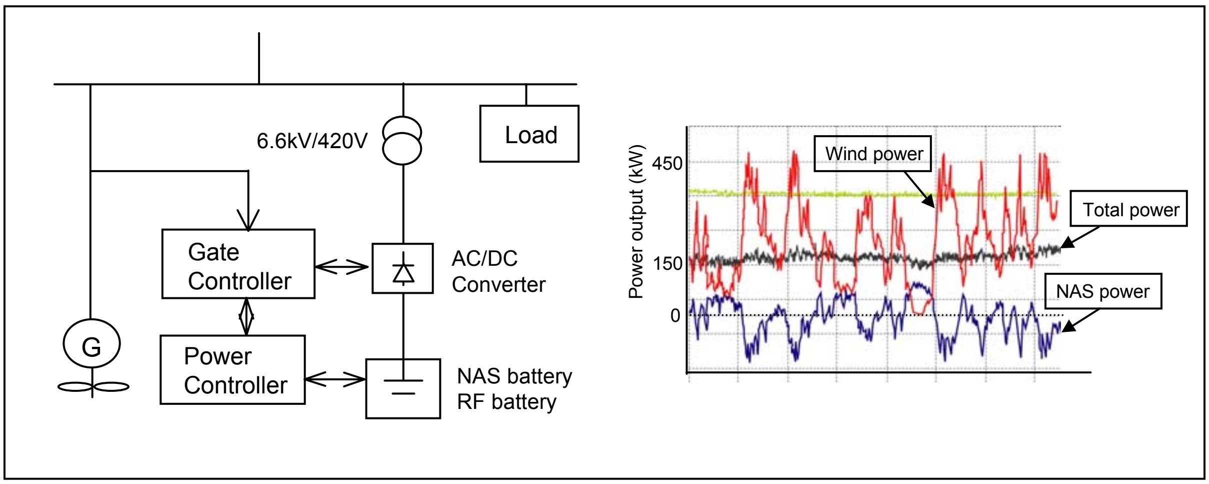

Figure 8 Output Leveling System with Storage Device

Impact on Network Upgrades

As with many other nations, Japan is now recognizing significant institutional challenges associated with developing consistent standards for interconnecting intermittent and distributed resources, including wind energy plants. While rigid standards for voltage and power quality have been adopted in Japan, the institutional factors associated with allocating the additional costs of network upgrades and the actual interconnections are still being worked out.

Regulation of the utility industry and independent power producers is under the common oversight of the Ministry of Economy, Trade, and Industry. However, when private renewable power producers are involved with traditional electric utilities, the question arises as to whether the costs of the wind plants' effect on transmission sizing should be borne by the private producer or by the traditional utility. Regulatory changes to address these challenges are underway and will be accomplished over the next several years.

USA Regional Wind Power Developments

A major report released earlier this year, developed for New York State Energy Research and Development Authority (NYSERDA), summarizes the different considerations of large-scale wind interconnection on transmission system planning, reliability and operations from systems in the United States and in Europe [54].

California and New York are the states furthest along in evaluating the overall systems impacts of substantially increasing wind as a part of their generation mixes. An excellent resource for a quick review of operation of wind plants in place today are the presentations from the Utility Wind Interest Group technical workshop in October of 2003 and their written report [70], [73].

Perhaps the most interesting recent development in the US markets is Bonneville Power Administration's (BPA) decision to offer storage and shaping services to wind plants. This service is available at a price of $6/MWh for up to 400 MW of wind. A key finding of the analysis behind this service offering was that for 1,000 MW of wind introduced into BPA's system, only 100 MW of additional regulation was required. This gave BPA comfort that it could use its available surplus capacity to support up to 400 MW of wind, even in dry years at seasonal minimums [71].

SYSTEM CHARACTERISTICS: EUROPE COMPARED TO WECC

In this section we identify the system characteristics of Europe that are relevant to wind integration impacts and compare those to the characteristics of the WECC and California.

Load Versus Generation Geography

For the highly interconnected European (UCTE) network [4] wind power projects and load centers are mostly well correlated and densely packed in Germany, the Netherlands, and portions of Spain. This means that wind generation is distributed among load centers, with minimal impacts on high voltage transmission networks at the 10 percent to 15 percent penetration levels.

In contrast, in the WECC, and especially California, the load centers are dispersed, with the largest load centers in greater Los Angeles vicinity and the San Francisco Bay Area. California imports roughly 20 percent of energy to meet demand. A large portion of the generation is far from these load centers, including remote Pacific Northwest and Interior West hydro and minemouth coal. This remote generation utilizes long-distance transmission.

Excess Capacity and Ancillary Services

In most parts of its electric system, the European Union has substantial excess capacity. Germany has up to 50 percent excess capacity in some areas [54].Congested bottlenecks are found in the interconnections between countries. These interconnections provide crucial energy transfers between countries, although for planning purposes in the future, countries will be expected to limit their reliance on their neighbors.

Also of note, because the European Union is composed of both large-load countries and small-load countries, location of large-scale (offshore) wind injection points becomes a very important consideration. Treating each country as responsible for its own renewables compliance as well as ancillary services may put smaller states at a disadvantage. Eltra reports that the Western Danish system, the whole of which has a peak load of 3,800 MW, will have a capacity requirement for 1,600 MW for ramping up and 1,050 MW for ramping down by 2005 [69].

In contrast to Germany’s large reserve margins, California’s reserve capacity margin has deflated to well under 20 percent due to regulatory restraint, creating a lack of demand for long-term contracts or a capacity market. In addition, the WECC's reliance on hydropower means that excess capacity varies substantially by season and year.

The California Independent System Operator, (CA ISO), is looking at changes to its procurement rules for ancillary services to acknowledge the issue of congestion and ancillary services delivery [72].

Interconnections and Congestion

In the UCTE network, the congested bottlenecks are currently at the country interconnections, which were not designed to handle large power transfers. Some countries have substantial imports and exports between them (e.g., Italy and Switzerland). Future planning by European states assumes zero imports, a policy constraint which may have large implications of power balancing between different countries with large wind penetration. Some of Europe's key power flows are:

- Norway's hydro serves parts of Denmark.
- The Nordic system has weak interconnections, concentrated load centers in the South, and mainly hydropower generation.
- Switzerland exports to Italy: the well-reported blackout on Sunday, September 28, 2003, was during low load operation in Italy when a key transmission interconnection tripped.

Summarized below is the power flow in the WECC's four major regions: NWPP, California, SW (Arizona, New Mexico, South Nevada) and RMPA:

- NWPP and SW export to California much of the year.
- Substantial congestion exists between northern and southern California.
- Using unloaded portions of the DC line between the Pacific Northwest and Los Angeles area is currently under investigation by the Public Renewables Partnership through a PIER contract.

The distances between generation and load centers in the WECC mean that wind, if sited in an area with good load following resources, could lower congestion. On the other hand, like any other resource, if wind is sited on the wrong side of congestion, it may exacerbate the problem until transmission upgrades are performed.

Generation Mix and Size

In the European Union, especially in Germany, many of the major nuclear generation resources are scheduled for retirement. Replacement of these generation sources with wind power is the impetus behind the guaranteed, preferential feed-in tariff. Now facing a large system with wind capacity exceeding 20 percent of peak load, system stability in Germany is becoming a limiting factor. E.ON Netz is requiring extra connection fees and higher connection standards for wind farms. Balancing energy is starting to become more costly. As a result, the Germans are looking at storage, e.g., increasing hydro reservoir capacity by several times to accommodate wind.

Most base-load coal, hydro, and nuclear power plants are currently in the 500-1,000 MW capacity range. The European Union does not yet use smaller gas generating plants to do power flow balancing on a large scale. In the last two years, Europe has added between roughly 5,500 MW and 6,000 MW of wind each year, mostly in Germany and Spain.

In the WECC, large hydro generation offers a good load following option for wind power, but much of the hydro resources are on the wrong side of the congested network relative to California's large load areas. Hydro is also constrained seasonally and environmentally and requires back up for dry years.

The WECC has baseload plants similarly sized to those in Europe. However, the WECC has an abundance of new gas plants and California has added gas peaking plants offering load following capabilities that complement wind generation. These new load following gas fueled generating plants can be used to balance the long-term power fluctuations from the wind much better that prior generations of gas plants because they are designed for increased start-stop cycles. The exhausts of these plants are also much cleaner compared to older plants during start-up, improving the emissions related to use for load following relative to older plants.

Wind Regime Diversity

In Europe, the Baltic and North Sea microclimates have different wind regimes with typically a six hour lag between them. Northern Germany has fairly uniform weather patterns, similar to the weather patterns experienced by wind plants in western Texas. The individual size of wind plants in Germany range from 10 MW to 100 MW.

The WECC weather system has a diversity of wind regimes, although within a congestion zone, there will be less diversity. Although most wind plants are sized at 200 MW or less, a resource in aggregate, such as the Tehachapi mountains wind resource area in California, could exceed 1,000 MW, entering the system at one or a few substations.

Permitting out-of-state wind may be beneficial to California for RPS compliance for the following reasons: a) ancillary services costs may be lower with high WECC wind penetrations if wind regime diversity is achieved, b) a broader set of generation resources will be available to support wind with ancillary services.

System Characteristics Conclusions

The WECC and California differ from Europe's electrical system in some important characteristics:

1. The WECC has load centers far from some of its major generation resources, whereas until recently Europe has had most of its wind resource developed in a dispersed manner, close to load, similar to its conventional resources.
2. California's reserve margin rules are being developed at the Public Utilities Commission, but contrast with Germany's high reserve margin.
3. Inadequate transmission in the WECC means that congestion occurs when trying to move energy from one major region to another, even within a single control area like the California ISO. Europe's congestion issues are at the inter-country level, but have similar implications within a zone once penetration reaches the limits of ancillary services available from reserves, as is happening in northwest Germany.

Europe's move to harness its offshore wind resources has set up a new set of issues dealing with large-scale wind generation injected into a few points in the grid. Although closer to load centers than the wind resources at Tehachapi, the European analysis underway and recently completed will have relevance to California's remaining untapped major wind resource areas [45].

WINDPOWER IMPACTS ON OTHER GENERATION PLANTS

In this section we summarize the operating characteristics of thermal and hydropower resources and how they can address the potential impacts of large-scale intermittent generation on the WECC and California system operations and generating mix.

In order to evaluate the effects of wind power on existing operating units, the following items should be considered:

1. Ability to forecast wind power output (hourly and day-ahead)
2. Ability to forecast system load (hourly and day-ahead)
3. Regulation horizon (minute-to-minute)
4. Load following horizon (normally hourly in 5-10 minute increments)
5. Day-ahead unit commitment
6. Amount of wind generation being added
7. Geographical diversity of the wind parks in the system
8. Constraints to import/export power to/from the system
9. Total number, size and type of units in the system
10. System reserve requirements and reserve margins

A review of studies and documentation indicates that sufficient work has been done on the issues listed above to present a realistic assessment of the overall effects the addition of various amounts of wind power will have on a large transmission system containing a diversified (size and type) mix of units. This discussion will be limited to the California ISO (CA ISO) Control Area and the potential effects of adding wind power in that area. A summary of the combined impacts of the above items and their expected effects on the regulation, operating reserves, planning reserves, reliability, and plants operating in the CA ISO Control Area is presented below.

The California Independent System Operator System

The CA ISO Control Area has a total of over 54,000 MW of installed capacity (before generator de-rates for availability) and the ability to import in excess of an additional 5,800 MW. The CA ISO 2004 Summer Assessment forecasted a peak load of 44,422 MW with a minimum projected planning reserve of 16.4 percent and a corresponding operating reserve of 2,750 MW. Approximately 32,700 MW are thermal units, 2,600 MW are wind, with the remaining 18,700 MW consisting of a mix of hydro, pumped storage and solar.

The 2004 base scenario forecast wind capacity for California during summer peaks is only 235 MW (9.0 percent of the installed wind capacity), which corresponds to the average measured wind capacity observed when loads exceeded 40,000 MW in the CA ISO Control Area for 2003. The adverse scenario forecasts “0” MW and the favorable scenario forecasts 675 MW (25.9 percent of the installed wind capacity).

A review of certain available data relating to the effects of wind power additions on existing systems were performed based on studies indicated in the Reference Section of this report [6],[11],[32],[36],[39],[45].

Wind turbine output is dependent on wind speed and consistency, which cannot be predicted with a high degree of accuracy more than a day in advance and can fluctuate minute-to-minute. In a control area, day-ahead decisions (unit commitment) involve decisions regarding which units to turn on and when to do so. System operators handle daily load variations (load following) by maintaining sufficient load following operating reserve capacity (spinning and non-spinning reserve) and dispatching the associated energy on an economic basis. Minute-to-minute fluctuations (regulation) in load are controlled by increasing or decreasing the output of a subset of the generators on-line and synchronized to the network. Such units have a computer-controlled automatic generation control (AGC) system that signals these units to match changing load conditions.

Windpower Operating Reserve and Regulation Impacts

We can look at the impact of intermittent resources, like wind, on system and plant operations and compare the impacts to those associated with load volatility on the system: load forecasting error affects operating reserves while short-term fluctuations in load affect regulation. Small, short-term impacts on system operation will affect the plants providing regulation, increasing or decreasing their energy output within their operating boundaries. Larger impacts over the course of hours or days will impact the units committed to operating reserves, spinning and non-spinning. Load under-forecasting error, a thermal unit tripped off-line or transmission failures preventing power imports each roughly equate to a drop in production of a wind plant relative to what was forecast a day ahead of time. In any of these cases, depending on the size of the impact, units may be ramped up or added to the system.

Using summer peak values and some simplifying approximations, we can estimate the relative effects of load forecasting error versus wind capacity forecasting error on unit commitment. Conservatively assuming a 7 percent operating reserve requirement[1] and a 3 percent error in day-ahead load forecasting on a predicted heavy-load, 40,000 MW peak day, the amount of operating reserve error will be approximately 84 MW relative to carried operating

[1] The WECC requires a 6.6 percent operating reserve margin, but the way it is calculated is not a straight percentage of load.

reserve of 2,800 MW[2]. Assuming a 50 percent error in wind capacity forecasting during the same period and using the base scenario wind forecast of 235 MW yields an operating reserve error of about 7 MW. In the favorable scenario wind forecast, a 50 percent error in wind capacity forecasting would yield an operating reserve error of 24 MW. This explains why even large errors in wind forecasting of California's existing wind resources have little effect on the CA ISO system.

In addition, to understand the full impact of forecasting error for wind relative to load, we must look at the errors in combination. If the load forecasting error is similar in shape to the wind forecasting error, the wind could amplify the load forecasting error. Based on our review of the industry's analysis to date, that is not the case. If the wind forecasting error is not correlated with load forecasting error, at small volumes, the wind error is "lost in the noise" relative to the load forecasting error. At larger volumes, the wind is likely to be more geographically disperse, dampening the effect of load forecasting error for any individual plant.

If we assume that 6,000 MW of new wind generation are added to the CA ISO Control Area (8,611 MW when combined with existing wind capacity) as demand grows, generation plant retirements occur, with some attention paid to geographical diversity and under similar assumptions used for the 2004 Summer Assessment Base Case, the amount of additional operating reserve requirements attributable to wind would only increase by about 33 MW. The projected planning reserve (the capacity over and above the capacity required to meet peak demand without any reductions for forced outages) would benefit by an increase from 16.4 percent to 17.6 percent under this scenario.

Examining the costs associated with load following, information suggests that geographical dispersion of the wind resources, for any amount of wind additions tend to reduce the amount of incremental load following requirements due to those additions. The larger the amount of wind addition to a system, the more significant the role geographical dispersion plays in reducing the amount of incremental load following requirements. Although these costs varied widely across the information reviewed, in no case were they prohibitive.

Because of the lack of correlation between load forecasting and wind forecasting error, costs associated with regulation requirements in all cases reviewed were very small to negligible. In large systems the cost ranged from $0 to $0.19/MWh.

Windpower Impacts on Reliability and System Operations

Regarding system reliability, all information reviewed indicates that generation systems can operate reliably with significant amounts of wind capacity installed.

[2] 40,000 MW * 3 percent load forecast error * 7 percent operating reserve = 84 MW

Recent studies by PacifiCorp and We Energies included wind penetration of up to 20 percent on their systems, according to a review of the study summaries. Based on all information reviewed, it appears that the issue of assigning even large amounts of wind power to a system is one of increased operating costs, not reliability.

Hydropower generators are often used for regulation and load following, but the availability of hydro energy is limited by weather, time of the year, environmental restrictions, and opportunity costs. When hydro resources are the marginal unit or are being used for operating reserves or regulation, changes in wind generation will increase or decrease a hydro unit's generation output.

The thermal units on the system that would be used for operating reserves consist of steam plants, combined cycle plants, and gas turbines. These units vary in their ramp rates and minimum outputs, but it is conservative to assume ramp rates of 4 percent-7 percent of Maximum Continuous Rating (MCR) per minute for steam plants and combined cycle units with faster ramp rates for gas turbine units. Minimum loads can vary but in general, for stable operation, gas turbines can operate with minimum loads down to 20 percent-25 percent MCR and steam plants as low as 15 percent MCR.

Because plants are configured differently (with/without steam bypass systems, with/without bypass stacks, aero-derivative vs. Frame machines, etc.) and because many units will be on-line and used for load following, system reliability and load following capability will not be affected by the addition of a significant amount of wind generation.

Windpower Impact on System Generation Mix

Assuming load growth continues, capacity additions will be required to serve that increase and to meet the required reserve margins. The decision to build a wind plant will depend on the overall projected economics including tax credits, economic incentives, and the ability to repay the initial investment plus a suitable, risk weighted return to the investors. To some extent, as wind capacity is built, it will displace other new units being built in its place.

Although the capacity factor assumed for wind at peak demand in the CA ISO Control Area has been approximately 9 percent, on an annual basis, the historical annual average capacity factor for wind power is closer to 25 percent. Based on public data on projects proposed in California and the WECC over the past several years, new wind projects are likely to have capacity factors in the 35-40 percent range.

Since the production cost of wind is essentially zero (no fuel cost), once built, wind power will operate and contribute to the grid whenever it is available. This means that for every 1,000 MW of new installed wind power generation, conservatively 3 million MWh per year of energy otherwise generated will be displaced.[3]

Wind generated off-peak, most likely displaces lower operating-cost base-load or intermediate-load units. Wind generated on-peak most likely displaced higher-cost peak or super-peak power. When hydro units are on the margin, water is retained for later use, or spilled if reservoir capacity or environmental constraints require flow to be maintained.

It would be reasonable to expect that the addition of large amounts of wind generation to a system would have some economic and physical impact on merchant plants in the medium to long run. If the marginal units are used less, fixed and capital costs are not being recovered in the hours it is run, or through other financial structures, which is likely to cause the generation owner to retire the unit. The magnitude of the impact is difficult to estimate because it is also dependent on the existing economics of the impacted merchant units, fuel prices, retirement of existing units, output of hydro units, rules still under development regarding generation adequacy, and other factors.

[3] 1,000 MW x 0.35 x 8760 hours/year.

ACRONYMS

AC	alternating current
AGC	automatic generation control
AWEA	American Wind Energy Association
BPA	Bonneville Power Administration
CA ISO	California Independent System Operator
CHP	combined heat and power
CPUC	California Public Utilities Commission
DC	direct current
DOE	U.S. Department of Energy
EEG	Germany’s renewable energy law (Erneuerbare-Energien-Gesetz)
EPCO	Electric Power Company
EWEA	European Wind Energy Association
FACTS	Flexible AC Transmission Systems
HVDC	high-voltage direct current
kV	kiloVolts
MCR	maximum continuous rating
MW	Megawatt
MWh	Megawatt hour
NPP	Nordic Power Pool
NWPP	Northwest Power Pool
NYSERDA	New York State Energy Research and Development Authority
PCC	partial private circuit
PRP	program responsible party
RF	redox flow
RMPA	Rocky Power Mountain Area
ROTES	Rotary Energy Storage System
RPS	Renewables Portfolio Standard
STATCOM	Static Compensator
SVC	static var compensator
UCTE	Union for the Co-ordination of Transmission of Electricity
VSG	variable speed generation
WEC	Wind Energy Conversion
WECC	Western Electricity Coordinating Council

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